

# Scrutinizing the $ZW^+W^-$ vertex at the Large Hadron Collider at 7 TeV

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## Abstract

We analyze the potential of the CERN Large Hadron Collider running at 7 TeV to search for deviations from the Standard Model predictions for the triple gauge boson coupling  $ZW^+W^-$  assuming an integrated luminosity of  $1 \text{ fb}^{-1}$ . We show that the study of  $W^+W^-$  and  $W^\pm Z$  productions, followed by the leptonic decay of the weak gauge bosons can improve the present sensitivity on the anomalous couplings  $\Delta g_1^Z$ ,  $\Delta \kappa_Z$ ,  $\lambda_Z$ ,  $g_4^Z$ , and  $\tilde{\lambda}_Z$  at the  $2\sigma$  level.

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Recently the CERN Large Hadron Collider (LHC) started a run with center-of-mass energy of 7 TeV and plans to accumulate an integrated luminosity of  $\simeq 1 \text{ fb}^{-1}$ . This new high energy frontier allow us to further test the Standard Model (SM), as well as, to check for its possible extensions. In particular, within the framework of the SM, the structure of the trilinear and quartic vector-boson couplings is completely determined by the  $SU(2)_L \times U(1)_Y$  gauge symmetry.

Thus the study of these interactions can either lead to an additional confirmation of the model or give some hint on the existence of new phenomena at a higher scale [1]. The triple gauge–boson vertices (TGV’s) have been probed directly at the Tevatron [2] and LEP [3] through the production of vector–boson pairs and the experimental results agree with the SM predictions, see Table 1. Moreover, TGV’s contribute at the one–loop level to the  $Z$  physics and consequently they can also be indirectly constrained by precision electroweak data [5]. At the LHC, the TGV’s will be subject to a more severe scrutiny via the production of electroweak gauge boson pairs, *e.g.*  $W\gamma$  and  $WZ$ . Running at 14 TeV center-of-mass energy and with 30–100  $fb^{-1}$  integrated luminosity it will probe these couplings at the few percentage level; see Ref. [6] for a recent update.

In this work we assess the potential of the LHC already running at 7 TeV to probe deviations from the SM prediction for the  $ZW^+W^-$  interaction through the reactions

$$pp \rightarrow W^+W^- \rightarrow \ell^+\ell'^- E_T \quad (1)$$

$$pp \rightarrow W^\pm Z \rightarrow \ell'^\pm \ell^+ \ell^- E_T \quad (2)$$

where  $\ell^{(\prime)} = e$  or  $\mu$ .

The most general form of the  $ZW^+W^-$  vertex compatible with Lorentz invariance is given by the effective Lagrangian [7]

$$\begin{aligned} \mathcal{L}_{\text{eff}}/g_{WWZ} = & +ig_1^Z \left( W_{\mu\nu}^\dagger W^\mu Z^\nu - W_\mu^\dagger W^{\mu\nu} Z_\nu \right) + i\kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} \\ & + i\frac{\lambda_Z}{M_W^2} W_{\rho\mu}^\dagger W_\nu^\mu Z^{\nu\rho} + g_5^Z \epsilon^{\mu\nu\rho\sigma} (W_\mu^\dagger \partial_\rho W_\nu - \partial_\rho W_\mu^\dagger W_\nu) Z_\sigma \\ & - g_4^Z W_\mu^\dagger W_\nu (\partial^\mu Z^\nu + \partial^\nu Z^\mu) + i\tilde{\kappa}_Z W_\mu^\dagger W_\nu \tilde{Z}^{\mu\nu} + i\frac{\tilde{\lambda}_Z}{M_W^2} W_{\sigma\mu}^\dagger W_\nu^\mu \tilde{Z}^{\nu\sigma} \end{aligned} \quad (3)$$

where  $Z^{\mu\nu} = \partial^\mu Z^\nu - \partial^\nu Z^\mu$  and  $\tilde{Z}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} Z_{\rho\sigma}$ .  $g_{WWZ} = -e \cot \theta_W$  and  $\theta_W$  is the weak mixing angle. The couplings  $g_1^Z$ ,  $\kappa_Z$  and  $\lambda_Z$  are C and P conserving,  $\tilde{\kappa}_Z$  and  $\tilde{\lambda}_Z$  are P odd and violate CP, while  $g_4^Z$  violates C and CP and  $g_5^Z$  violates C and P but is CP conserving. In the SM  $g_1^Z = \kappa_Z = 1$  and  $\lambda_Z = g_4^Z = g_5^Z = \tilde{\kappa}_Z = \tilde{\lambda}_Z = 0$ .

In presence of these anomalous couplings the cross sections for the processes  $pp \rightarrow \ell^+\ell'^- E_T$  and  $pp \rightarrow \ell^\pm \ell'^+ \ell'^- E_T$  take the form

$$\sigma = \sigma_{\text{SM}} + \sum_i \sigma_{\text{int}}^i g_{\text{ano}}^i + \sum_{i,j \geq i} \sigma_{\text{ano}}^{ij} g_{\text{ano}}^i g_{\text{ano}}^j, \quad (4)$$

where  $\sigma_{\text{SM}}$ ,  $\sigma_{\text{int}}^i$ , and  $\sigma_{\text{ano}}^{ij}$  are, respectively, the SM contribution, the interfer-

couplings	PDG bounds	indirect limits	Unit. $W^+W^-$	Unit. $W^\pm Z$
$\Delta g_1^Z$	$-0.016^{+0.022}_{-0.019}$	$[-0.051, 0.0092]$	2.7	0.22
$\Delta \kappa_Z$	$-0.076^{+0.059}_{-0.056}$	$[-0.050, 0.0039]$	0.22	3.5
$\lambda_Z$	$-0.088^{+0.060}_{-0.057}$	$[-0.061, 0.10]$	0.15	0.14
$g_5^Z$	$-0.07 \pm 0.09$	$[-0.085, 0.049]$	2.7	1.7
$g_4^Z$	$-0.30 \pm 0.17$	—	2.7	0.22
$\tilde{\kappa}_Z$	$-0.12^{+0.06}_{-0.04}$	—	2.7	3.5
$\tilde{\lambda}_Z$	$-0.09 \pm 0.07$	—	0.15	0.14

Table 1

Available limits on the anomalous TGV couplings. The first column contains a compilation of the direct searches performed by the Particle Data Group [4]. The indirect bounds are presented in the second column [5] where the entries not evaluated in the literature are marked as —. The third and fourth columns contain the bounds derived from the processes  $qq \rightarrow W^+W^-$  and  $W^\pm Z$  [13] imposing that unitarity is satisfied for energies below 2 TeV.

ence between the SM and the anomalous contribution, and the pure anomalous ones. For the CP violating couplings  $\sigma_{\text{int}}^i$  vanishes.

SM contributions to  $pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$  include electroweak (EW) processes leading to this final state – such as  $W^+W^-$  production or  $ZZ$  production with one  $Z$  decaying in charged leptons and the other in neutrinos – and  $t\bar{t}$  production with the top quarks decaying semi-leptonically. For  $pp \rightarrow \ell^\pm \ell'^+ \ell'^- \cancel{E}_T$  the main SM backgrounds are the EW production of  $W^\pm Z$  pairs and  $ZZ$  production with the subsequent decays of the  $Z$ 's into leptons when one charged lepton escapes detection. An additional background comes from  $t\bar{t}$  production if the semi-leptonic decay of a  $b$  gives rise to an isolated charged lepton.

The signal and backgrounds were simulated at the parton level with full tree level matrix elements generated with the package MadEvent [8] conveniently modified to include the anomalous TGV's. We employed CTEQ6L parton distribution functions [9] throughout. We took the electroweak parameters to be  $\alpha_{em} = 1/132.51$ ,  $m_Z = 91.188$  GeV,  $m_W = 80.419$  GeV, and  $\sin^2 \theta_W = 0.222$ , which was obtained imposing the tree level relation  $\cos \theta_W = m_W/m_Z$ . We simulated experimental resolutions by smearing the energies (but not directions) of all final state charged leptons with a Gaussian error  $\Delta(E)/E = 0.02/\sqrt{E}$ . We also included in our analysis a 90% lepton detection efficiency.

We began our analysis of processes (1) and (2) by imposing some basic acceptance cuts for the charged leptons and missing energy

$$p_T^\ell \geq 10 \text{ GeV} \quad , \quad |\eta_\ell| < 2.5 \quad , \quad \Delta R_{\ell\ell} \geq 0.4 \quad , \quad \cancel{p}_T \geq 10 \text{ GeV} \quad (5)$$

where  $\eta_\ell$  is the charged lepton pseudo-rapidity.

For  $pp \rightarrow \ell^+ \ell^- \cancel{E}_T$  events with the two leptons of the same flavor we further required that the lepton pair invariant mass ( $M_{\ell\ell}$ ) is not compatible with a  $Z$  production, *i.e.*

$$|M_{\ell\ell} - M_Z| > 10 \text{ GeV} . \quad (6)$$

Furthermore the top quark pairs are a potentially large background due to its production by strong interactions. To further suppress these events we vetoed the presence of central jets with

$$p_T^j > 20 \text{ GeV} \quad \text{and} \quad |\eta_j| < 3 . \quad (7)$$

For  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$  in the case with only a pair of same flavor different sign leptons (this is,  $\ell' \neq \ell$ ) we demanded that the invariant mass of the equal flavor lepton pair is compatible with the  $Z$  mass, *i.e.*

$$|M_{\ell\ell} - M_Z| < 10 \text{ GeV} , \quad (8)$$

The presence of just one neutrino in the final state of this channel permits the reconstruction of its momentum by imposing the transverse momentum conservation and requiring that the invariant mass of the third lepton and the neutrino is the  $W$  mass

$$M_{\ell'\nu} = M_W . \quad (9)$$

This procedure exhibits a twofold ambiguity on the neutrino longitudinal momentum. In our analysis we kept only events that possess a solution to the neutrino momentum.

Conversely when the three leptons have the same flavor we demanded that one opposite sign lepton pair satisfies (8) and the third lepton and the missing transverse momentum reconstructs a  $W$  as in (9). We further required that the invariant mass of the third lepton and the lepton of opposite charge used to reconstruct the  $Z$  is not compatible with a  $Z$ , therefore complying with (6). The top pair background to  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$  after cuts (5) and (8)–(9) (plus (6) for  $\ell' = \ell$ ) is already very suppressed since it requires that one of the isolated leptons originates from a  $b$  quark semi-leptonic decay. Vetoing any central jet activity, as in Eq. (7) renders the  $t\bar{t}$  cross section negligible.

We present in Table 2 the cross sections of the SM backgrounds and anomalous contributions to process  $pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$  after the cuts (5)–(7) and  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$  after the cuts (5) and (7)–(9) (plus (6) for  $\ell' = \ell$ ). For  $pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$  the cut (7) is very important to tame the dangerous  $t\bar{t}$  background whose cross section is 3.9 pb when we remove this cut. For simplicity we have only considered one non-vanishing anomalous vertex at a time. This simplifying hypothesis can be consistently made when the integration of the heavy degrees of free-

$\sigma_{\text{SM}} \text{ (fb)}$		$\sigma_{\text{ano}} \text{ (fb)}$				$\sigma_{\text{ano}} \text{ (fb)}$		
		$\sigma_{\text{int}} \text{ (fb)}$				$\Delta\sigma_{\text{ano}} \text{ (fb)}$		
$pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$								
$\ell^+ \nu_\ell \ell'^- \nu_{\ell'}$	$t\bar{t}$	$\Delta g_1^Z$	$\Delta \kappa_Z$	$\lambda_Z$	$g_5^Z$	$g_4^Z$	$\tilde{\kappa}_Z$	$\tilde{\lambda}_Z$
824.	11.1	254.	2540.	5750.	163.	219.	412.	6030.
		-55.7	-166.	-22.1	15.1	68.8	-89.2	152.
$pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$								
$\ell^+ \ell^- \ell'^{\pm} \nu$	$ZZ$	$\Delta g_1^Z$	$\Delta \kappa_Z$	$\lambda_Z$	$g_5^Z$	$g_4^Z$	$\tilde{\kappa}_Z$	$\tilde{\lambda}_Z$
63.0	2.32	1280.	65.4	2290.	391.	1020.	77.6	2390.
		-106.	-21.3	-24.3	-7.2	-20.2	-2.2	-10.0

Table 2

Cross sections for the process  $pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$  after the cuts (5)–(7) and  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$  after the cuts (5) and (7)–(9) (plus (6) for  $\ell' = \ell$ ). We denote by  $ZZ$  the process  $pp \rightarrow \ell^+ \ell^- \ell'^{\pm} [\ell'^{\mp}]$  where  $[\ell'^{\pm}]$  is a charged lepton that escapes detection. In all cases the results include the charge lepton detection efficiency. For the CP violating couplings we provide the result for  $\Delta\sigma_{\text{ano}}$ , see Eq. (13).

dom associated to a new physics leads to scenario where the  $SU(2)_L \times U(1)_Y$  symmetry is realized non-linearly in the low energy effective Lagrangian. If the low energy remains of the new physics are described by a linear realization of the  $SU(2)_L \times U(1)_Y$  there will be relations between the anomalous TGV's; see, for instance, reference [10].

The normalized spectra of the SM and the anomalous contributions for some relevant kinematic variables are displayed in Figure 1. For  $pp \rightarrow \ell^+ \ell'^- \cancel{E}_T$  we have defined the transverse mass  $M_T^{WW}$  as:

$$M_T^{WW} = \left[ \left( \sqrt{(p_T^{\ell^+ \ell'^-})^2 + m_{\ell^+ \ell'^-}^2} + \sqrt{\vec{p}_T^2 + m_{\ell^+ \ell'^-}^2} \right)^2 - (\vec{p}_T^{\ell^+ \ell'^-} + \vec{p}_T)^2 \right]^{1/2} \quad (10)$$

where  $\vec{p}_T$  is the missing transverse momentum vector,  $\vec{p}_T^{\ell^+ \ell'^-}$  is the transverse momentum of the pair  $\ell^+ \ell'^-$  and  $m_{\ell^+ \ell'^-}$  is the  $\ell^+ \ell'^-$  invariant mass.

For  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- \cancel{E}_T$  we define  $p_{TZ}$  as the transverse momentum of the opposite sign equal flavor leptons verifying (8). Furthermore, it is possible to reconstruct the neutrino momentum, and consequently, we can evaluate the total  $\ell\ell\ell\nu$  invariant mass (which we label  $M_{WZ}$ ) that takes two possible values for each event. In the lower right panel of Fig. 1 we show the distribution in this variable where each of the solutions have been given weight 1/2.

Figure 1 illustrates the well-known fact that the anomalous contributions en-

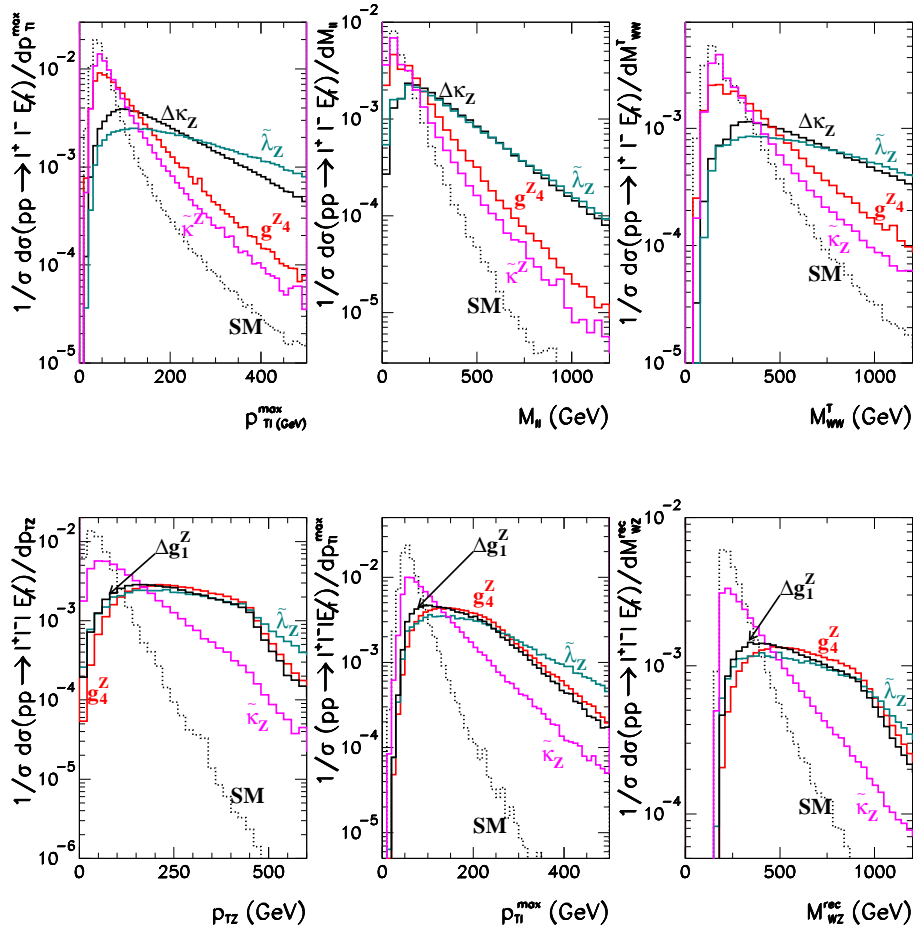


Fig. 1. Normalized spectra for some relevant kinematic variables for the SM and some of the anomalous TGV's for  $pp \rightarrow \ell^+ \ell^- E_T$  (upper panels) and  $pp \rightarrow \ell'^{\pm} \ell^+ \ell^- E_T$  (lower panels). The upper panels show the distribution in transverse momentum of the hardest lepton (left panel), dilepton invariant mass (central panel) and reconstructed  $WW$  transverse invariant mass (right panel). The lower panels show the transverse momentum of the  $Z$  (left panel), hardest lepton transverse momentum (central panel), and reconstructed  $WZ$  transverse invariant mass (right panel).

hance the cross section at higher collision energies (eventually leading to perturbative unitarity violation) and that this behaviour can be well traced by either  $p_{T\ell}^{max}$ ,  $M_{\ell\ell}$ ,  $M_{WW}^T$ ,  $p_{TZ}$  or  $M_{WZ}$  respectively.

In order to extract the attainable sensitivity on anomalous TGV we analyzed for each kinematic variable shown in Fig. 1 the choice of cut that maximizes the sensitivity for deviations in the TGV's. Given the limited statistics of the 7 TeV LHC run we do not attempt to make a fit to the distributions and use instead as unique variable the total number of observed events above a certain minimum cut for each of the variables. In each case we assumed

	$W^+W^-$ $2\sigma$ limits		$W^\pm Z$ $2\sigma$ limits	
	No form factor	$\Lambda = 3$ TeV	No form factor	$\Lambda = 3$ TeV
$\Delta g_1^Z$	$[-0.33, 0.56]$	$[-0.35, 0.59]$	$[-0.055, 0.094]$	$[-0.061, 0.11]$
$\Delta \kappa_Z$	$[-0.088, 0.11]$	$[-0.10, 0.14]$	$[-0.27, 0.55]$	$[-0.29, 0.61]$
$\lambda_Z$	$[-0.055, 0.056]$	$[-0.074, 0.075]$	$[-0.051, 0.054]$	$[-0.060, 0.064]$
$g_5^Z$	$[-0.53, 0.51]$	$[-0.56, 0.55]$	$[-0.18, 0.19]$	$[-0.19, 0.20]$
$g_4^Z$	$[-0.48, 0.48]$	$[-0.51, 0.51]$	$[-0.080, 0.080]$	$[-0.091, 0.091]$
$\tilde{\kappa}_Z$	$[-0.38, 0.38]$	$[-0.39, 0.39]$	$[-0.40, 0.40]$	$[-0.42, 0.42]$
$\tilde{\lambda}_Z$	$[-0.055, 0.055]$	$[-0.074, 0.074]$	$[-0.053, 0.053]$	$[-0.062, 0.062]$

Table 3

Attainable  $2\sigma$  bounds on anomalous TGV at the LHC at 7 TeV with  $1 \text{ fb}^{-1}$ .

that the total number of observed events is the one predicted by the SM at integrated luminosity of  $1 \text{ fb}^{-1}$ . The corresponding statistical uncertainty were obtained using Poisson or Gaussian statistics depending on whether the expected number of SM events was smaller or larger than 20. We performed our analysis of the channels  $pp \rightarrow \ell^+ \ell'^- E_T$  and  $pp \rightarrow \ell'^\pm \ell^+ \ell^- E_T$  independently.

We depict in Figure 2 the achievable  $2\sigma$  limits from  $pp \rightarrow \ell^+ \ell'^- E_T$  on some of the anomalous TGV as a function of the the minimum cut on the maximum transverse momentum of the leptons (left panels), dilepton invariant mass (central panels) and minimum reconstructed transverse invariant mass ( $M_{WW}^T$ ) in the right panels. As we can see from this figure the couplings  $\Delta \kappa_Z$ ,  $\lambda_Z$  and  $\tilde{\lambda}_Z$  possess a mild dependence on the kinematic cut while  $g_4^Z$  and  $\tilde{\kappa}_Z$  experience larger changes with the variation of the cuts. This can be understood from Fig. 1 that shows that  $g_4^Z$  and  $\tilde{\kappa}_Z$  distributions decrease much faster than the ones for  $\tilde{\lambda}_Z$ . We find that maximum sensitivity for any of the anomalous TGV is obtained from a minimum cut in transverse momentum of the hardest lepton with the optimum cut ranging between 50–200 GeV depending on the anomalous coupling considered. The corresponding attainable  $2\sigma$  bounds are listed in Table 3. Our results show that this channel can tighten the present direct bounds on  $\Delta \kappa_Z$ ,  $\lambda_Z$ ,  $g_4^Z$ , and  $\tilde{\lambda}_Z$ .

Correspondingly we show in Figure 3 the bounds from  $pp \rightarrow \ell'^\pm \ell^+ \ell^- E_T$  as a function of the minimum cut in either the  $Z$  transverse momentum (left panels), the hardest lepton transverse momentum (central panels), and the reconstructed  $WZ$  invariant mass (right panels). We find that a minimum cut in either of the transverse momentum variables (that of the  $Z$  or the hardest lepton  $p_T$ ) leads to the best sensitivity. The corresponding attainable  $2\sigma$  bounds are also listed in Table 3 that shows that this channel can improve the present direct constraints on the couplings  $\Delta g_1^Z$ ,  $\lambda_Z$ ,  $g_4^Z$  and  $\tilde{\lambda}_Z$ .

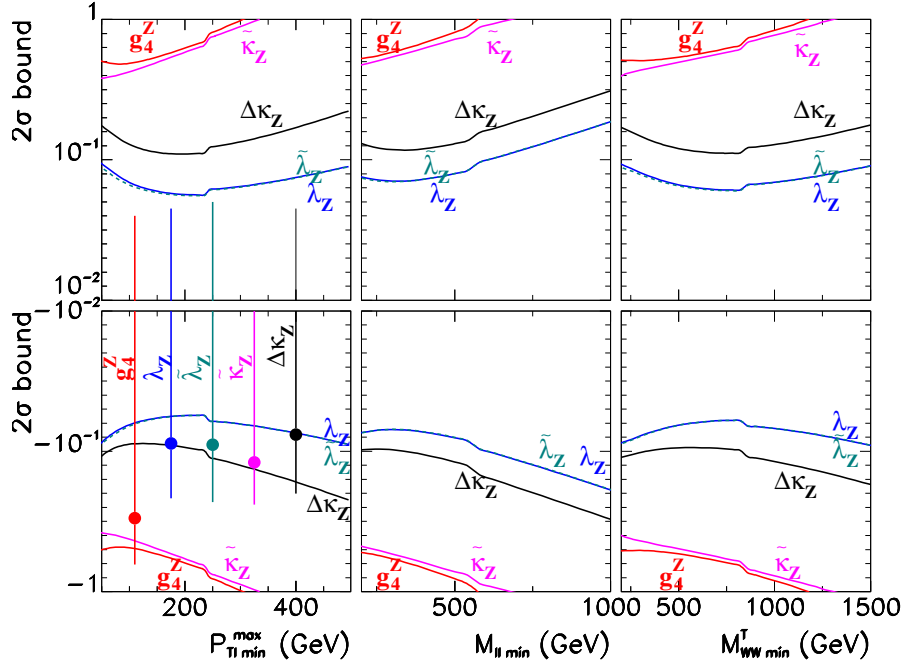


Fig. 2. Dependence of the upper (top panels) and lower (lower panels)  $2\sigma$  bounds achievable from the study of  $pp \rightarrow \ell^+ \ell^- E_T$  as a function of the cut on the minimum value on the hardest lepton transverse momentum (left panels), the dilepton invariant mass (central panels), and the reconstructed  $WW$  transverse invariant mass (right panels). The dashed curves correspond to  $\tilde{\lambda}_Z$  and are almost indistinguishable from the full blue lines corresponding to  $\lambda_Z$ . The presently allowed  $2\sigma$  ranges are indicated by the vertical lines in the left panels.

So far we have applied the same type of analysis to CP conserving or CP violating couplings. For these last ones their CP breaking nature can be addressed constructing some CP-odd or  $\hat{T}$ -odd observable by weighting the events with the sign of the relevant cross product of the measured momenta. For example, following Refs. [11, 12] we can define

$$\Xi_{\pm} \equiv \text{sign}[(\vec{p}_{\ell^+} - \vec{p}_{\ell^-})^z] \text{sign}(\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})^z \quad \text{for } pp \rightarrow \ell^+ \ell^- E_T, \quad (11)$$

$$\Xi_{\pm} \equiv \text{sign}(p_Z^z) \text{sign}(p_{\ell'} \times p_Z)^z \quad \text{for } pp \rightarrow \ell'^{\pm} \ell^+ \ell^- E_T, \quad (12)$$

where  $z$  is the collision axis. The CP-violating couplings give a non-vanishing contribution to the sign-weighted cross section

$$g_{\text{ano}}^i \Delta\sigma_{\text{ano}}^i \equiv \int d\sigma \Xi_{\pm}. \quad (13)$$

We present in Table 2 the values of the corresponding sign-weighted cross sections. The resulting number of sign-weighted events has to be compared with the statistical fluctuations from the SM events (which are sign symmetric). We find that given the existing bounds on  $\tilde{\kappa}_Z$ ,  $\tilde{\lambda}_Z^Z$  and  $g_4^Z$ , the study of these



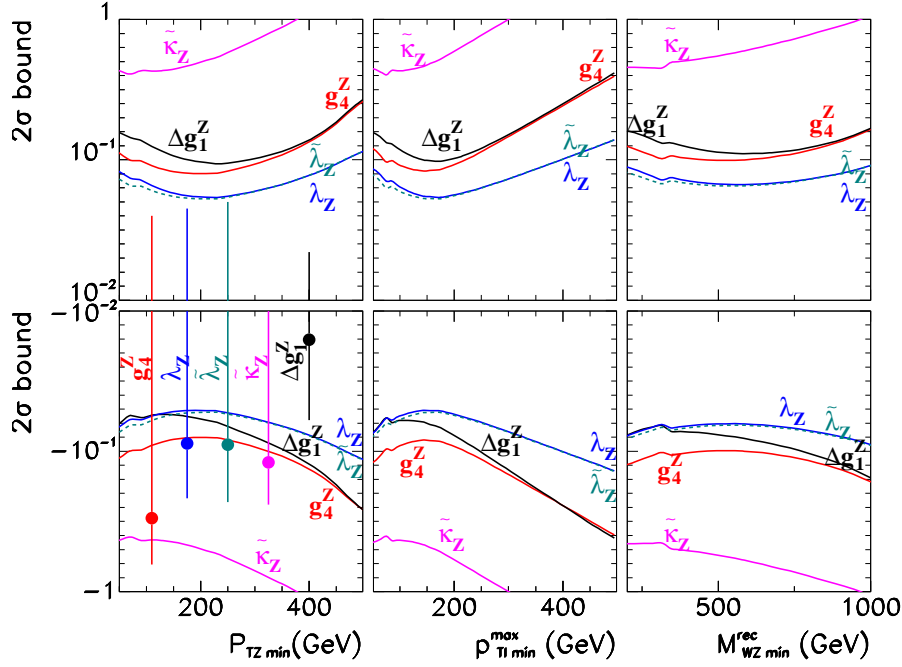


Fig. 3. Dependence of the upper (top panels) and lower (lower panels)  $2\sigma$  bounds from  $pp \rightarrow \ell'^{\pm}\ell^+\ell^- E_T$  a function of the cut on the minimum value on the  $Z$  transverse momentum (left panels), the hardest lepton transverse momentum (central panels), and the reconstructed  $WZ$  invariant mass (right panels). The dashed curves correspond to  $\tilde{\lambda}_Z$  and are almost indistinguishable from the full blue lines corresponding to  $\lambda_Z$ . The presently allowed  $2\sigma$  ranges are indicated by the vertical lines in the left panels.

events at the 7 TeV run of LHC is not precise enough to provide information on the CP properties of the anomalous couplings.

It is well known that the introduction of anomalous couplings spoils delicate cancellations in scattering amplitudes, leading to their growth with energy and, eventually, to unitarity violation above a certain scale  $\Lambda$ . The way to cure this problem that is being used in the literature is to introduce an energy dependent form factor that dumps the anomalous scattering amplitude growth at high energy, such as

$$\frac{1}{(1 + \frac{\hat{s}}{\Lambda^2})^2} \quad (14)$$

where  $\sqrt{\hat{s}}$  is the center-of-mass energy of the  $WW$  or  $WZ$  pair. Here we advocate that the need to introduce a form factor at the 7 TeV run of LHC is marginal because the center-of-mass energy for the contributing sub-process in (1) and (2) is  $\lesssim 2$  TeV, and the unitarity bounds on the anomalous TGV stemming from these processes are much weaker than the ones that we obtain; see the fourth and fifth columns of Table 1. In principle one may worry about the corresponding unitarity violation in longitudinal  $VV$  ( $V = W^{\pm}$  or  $Z$ ) scat-

tering which can lead to stronger bounds on the TGV since they can lead to a scattering amplitude which grows as  $\hat{s}^2$ . However, the actual energy behaviour of the scattering amplitude in longitudinal gauge boson scattering depends strongly on the assumptions about the quartic gauge boson couplings [14]. In particular, if there is a mechanism relating the quartic and triple anomalous contributions the  $VV$  scattering unitarity bounds turn out to be similar to the ones in reference [13]. Altogether we find that within the bounds that we derive, unitarity is held up to  $\sqrt{\hat{s}} \simeq 3$  TeV. As a final consistency check we derive the bounds obtained if a form factor (14) was included with  $\Lambda = 3$  TeV. We show in Table 3 the changes in the  $2\sigma$  sensitivity.

Our analysis leaves some room for improvement. For instance, we considered only one kinematic distribution to extract the bounds, leaving out the possibility of optimizing the analysis for joint distributions or a binned maximum likelihood fit. Moreover, our calculations were carried out at the parton level with the lowest order perturbation theory. Certainly a full Monte Carlo analysis taking into account detector simulation, as well as, NLO QCD [15] and EW [16] is in order. Although QCD NLO corrections are potentially dangerous due to changes in  $p_T$  distributions, our jet veto cut (7) is enough to guarantee that the attainable limits are not significantly altered [15, 17]. In brief, we anticipate that our results should give a fair estimate of the LHC potential to study the  $ZW^+W^-$  vertex.

Summarizing, we have shown that the study of the processes (1) and (2) at the LHC with a center-of-mass energy of 7 TeV and an integrated luminosity of  $1 \text{ fb}^{-1}$  can improve the presently available direct limits on the  $Z$  anomalous couplings  $\Delta g_1^Z$ ,  $\Delta \kappa_Z$ ,  $\lambda_Z$ ,  $g_4^Z$ , and  $\tilde{\lambda}_Z$ . Due to the small integrated luminosity predicted for this initial run, the limits on these couplings will be only slightly more stringent than the present available ones. Nevertheless, the more precise results on  $\Delta g_1^Z$  and  $\lambda_Z$  will start to compete with the indirect limits coming from precision measurements; see Table 1.

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